

Search for the Neutron Electric Dipole Moment: Contributions from the Triangle Universities Nuclear Laboratory

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A significant fraction of the research effort at the Triangle Universities Nuclear Laboratory (TUNL) focuses on weak interaction studies and searches for physics beyond the Standard Model. One major effort is the development of a new experimental technique to search for the neutron electric dipole moment (nEDM) that offers the potential for a factor of 100 increase in sensitivity over existing measurements. The search for this moment has the potential to reveal new sources of time reversal (T) and charge-conjugation-and-parity (CP) violation and to challenge calculations that propose extensions to the Standard Model. We provide a brief overview of the experiment as a whole and discuss the work underway at TUNL as part of this effort.

I. INTRODUCTION

The Golub-Lamoreaux proposal[1] to measure the neutron electric dipole moment (nEDM) using ultracold neutrons (UCN) and polarized ^3He in a superfluid bath of helium is being developed by the nEDM Collaboration, a consortium of 21 institutions[2], and will be operated at the Spallation Neutron Source at Oak Ridge National Laboratory in Oak Ridge, TN. The Triangle Universities Nuclear Laboratory (TUNL) is playing a major role in the development of many key aspects of this experiment.

The experimental search for a neutron electric dipole moment has the potential to reveal new sources of time-reversal (T) and charge-conjugation-and-parity (CP) violation and to challenge calculations that propose extensions to the Standard Model. The goal of the experiment is to improve the measurement sensitivity of the nEDM by two orders of magnitude over the present experimental limit [3]. A successful measurement will impact our understanding of the physics of both weak and strong interactions. The physics goals of this experiment remain timely and are of significant importance [4].

The experiment is based on a magnetic-resonance technique: a magnetic dipole is rotated in a magnetic field. Polarized neutrons and polarized ^3He atoms are dissolved in a bath of superfluid ^4He at a temperature of < 450 mK. When placed in an external magnetic field, both the neutron and ^3He magnetic dipoles precess in the plane perpendicular to the magnetic field. The measurement of the neutron EDM involves measuring the difference in the precession frequencies of the neutrons and the ^3He atoms when a strong electric field is applied either parallel or anti-parallel to the magnetic field. In this comparison measurement, the neutral ^3He atom is assumed to have a negligible electric dipole moment and serves as a volume co-magnetometer.

In principle, this new type of nEDM experiment could achieve more than two orders of magnitude improvement in the experimental limit for the neutron EDM. This factor results from the possibility of an increased electric field due to the excellent dielectric properties of superfluid ^4He , an increase in the total number of ultracold neutrons stored, and an increased storage time for these UCNs. The current experimental nEDM bound ($d_n < 3 \times 10^{-26} \text{ e}\cdot\text{cm}$)[3], however, is limited by magnetic field systematics, particularly known as the geometric phase effect[5, 6]. The use of ^3He as a volume co-magnetometer is crucial to the minimization of this magnetic-field systematic[7, 8].

TUNL plays an active role in all aspects of the nEDM experiment, with our goals of addressing outstanding issues related to maximizing the sensitivity of the measurement, designing the experiment itself, and serving in key management positions. We are investigating the geometric phase effect, developing the data acquisition and slow controls system, designing the cryogenic environment of the experiment, simulating the spin transport of polarized ^3He , simulating the transport of neutrons, and developing an apparatus to study systematic effects simultaneously using polarized ^3He and ultracold neutrons. Brief discussions of these activities are presented below.

II. GEOMETRIC PHASE EFFECTS

In the large-scale neutron electric dipole moment apparatus, the interaction of the field $\vec{B}_{eff} \sim \vec{v} \times \vec{E}$ with magnetic field gradients will produce a frequency shift linearly proportional to the electric field. Known as the geometric phase effect and mimicking a true nEDM, this effect has emerged as a primary systematic error limiting the precision of the next generation of nEDM searches.

In the context of nEDM experiments, this effect was first investigated experimentally and theoretically by Pendelbury *et al.*[6] and later by Lamoreaux and Golub[7]. In a published work[8], we introduced an analytic form for the correlation function that determines the behavior of the frequency shift, and showed in detail how it depends on the operating conditions of the experiment. Using an analytic function for the case of gas collisions, we averaged over a Maxwellian velocity distribution to calculate the temperature dependence of the frequency shift for ^3He diffusing in superfluid ^4He . Solutions to the phase shift and relaxation rates for fields with arbitrary spatial dependence have recently been found for 2 and 3 dimensions valid for all mean free paths.

The results indicate that it may be possible to fine-tune the effect to a high degree by an appropriate choice of operating temperature. From an experimental point of view it is very appealing to try to make use of the zero crossings to reduce the systematic effects to zero. Our theoretical work indicates it is plausible to do this for ^3He , by tuning the temperature of the apparatus to take advantage of the $1/T^7$ dependence of the diffusion constant for ^3He in superfluid ^4He [9]. Specifically for the nEDM experiment, we have used our simulation results in combination with ^3He transport calculations to set the nominal operating temperature for the nEDM experiment of < 450 mK.

Experimentally, we have constructed an apparatus where polarized ^3He can be injected into a deuterated rectangular polystyrene cell filled with superfluid ^4He at $T \leq 500$ mK. Initial experiments were aimed at verifying the predicted depolarization rates of polarized ^3He within a measurement cell. We measured a depolarization probability per bounce of $\sim 1 \times 10^{-7}$ using NMR excitation and detection coils and superconducting constant-field and gradient coils[10, 11].

Since these initial measurements, we carried out a series of measurements of the appropriate correlation function at different densities. To compensate for the fact that the relaxation takes place at different frequencies, we ramped the magnetic field so that measurements could be made at a constant frequency. It is necessary to ramp the gradient on and off to enable measurements of the polarization as a function of decay time.

The geometric-phase-effect measurements rely on theoretical calculations that show one can determine the effect by measuring the T_1 relaxation rate of the ^3He polarization in a magnetic field gradient. Thus it is not required to measure directly the $(\vec{v} \times \vec{B})$ -induced frequency shift. If one applies a uniform magnetic field gradient $\partial B_z / \partial z$ large enough so that it dominates all other field gradients, the relaxation time T_1 can be determined by traditional NMR techniques, assuming wall relaxation can be neglected. This technique does not require an electric field and thus significantly simplifies the experiment. We have taken data on the geometric phase effect and are presently in the process of its analysis.

III. STUDIES OF SYSTEMATIC EFFECTS

The nEDM project has identified a new opportunity now available that is aimed to significantly reduce the risk to the project while shortening the time to a physics measurement. The PULSTAR UCN source, located on the campus of NC State University, will soon come online and become a world-class source of UCNs[12], comparable in intensity to existing sources at both the Institut Laue Langevin (ILL)[13] and Los Alamos National Laboratory (LANL)[14]. This source, coupled with the existing polarized ^3He capabilities at TUNL, will enable development of an ideal setup for investigating many UCN- ^3He interactions at cryogenic temperatures.

The apparatus is being developed with the primary goal of exploring key systematic effects for the nEDM experiment as well as performing characterization tests on a full-size measurement cell for the main nEDM apparatus. The design goal is to develop an apparatus that will allow tests of five key scientific areas outlined below to be performed in a single actual size nEDM measurement cell filled with liquid helium residing in a uniform magnetic field (without an electric field).

The basic idea of the apparatus is that a measurement cell filled with liquid ^4He at a temperature of $T < 450$ mK will be placed within a uniform magnetic field. Cryogenic conventional and superconducting magnetic shields will surround this geometry, as well as thermal radiation shields and finally a series of additional external conventional magnetic shields.

Several components must couple with the measurement cell in order to cool the sample, fill the cell with UCN, fill and remove the polarized ^3He , and detect the scintillation light from neutron capture. First, the cell

will be thermally anchored to the mixing chamber of a ^3He - ^4He dilution refrigerator to provide cooling. A fill line for the liquid helium will be thermally anchored to the refrigerator and allow helium gas to be condensed within the cell through a small capillary. A second line will extend from above the cryostat to the cell to allow polarized ^3He to be introduced within the cell. At the end of a measurement cycle, the unpolarized ^3He must then be removed from the liquid. UCN from the PULSTAR source will be transported to the cell through a series of guides and introduced into the cell through a valve similar in design to the actual nEDM valve. Light from the neutron capture scintillations will be wavelength shifted to visible wavelengths using deuterated fluors, transported away from the cell through acrylic lightguides, and detected using photomultiplier tubes. Pulses will be digitized and analyzed offline.

We have identified five key scientific areas where studies at TUNL can provide significant advances to the development and implementation of the nEDM project:

Measurement of Scintillations Due to the Relative UCN- ^3He Precession and Demonstration of the Critical Dressing Technique

The fact that the magnetic moments of the neutrons and ^3He are only 10 % different reduces the sensitivity to background fields by an order of magnitude. If the moments were exactly equal, there would be no effect at all. Unfortunately, we have no direct control over the physics responsible for the observed magnetic moments; however, these moments can be artificially modified by using ‘dressed spin’ techniques. In the presence of a strong oscillating magnetic field, the magnetic moment will be modified, or ‘dressed’, yielding an effective gyromagnetic ratio. With proper choice of magnetic fields, the magnetic moments of two species can be made equal.

In practice, the oscillating field is at right angles to the static field B_0 around which the spins are precessing. In the absence of the oscillating field, one would see an oscillation in the scintillation rate arising from neutron capture on ^3He at the difference in the precession frequencies. When the RF dressing field is applied, the effective magnetic moments become modified, and at the condition referred to as ‘critical dressing’, the two will have the same precession frequencies.

If the nEDM is non-zero, the neutron precession frequency will be shifted by an amount $2d_n E j_0(\gamma_n x)$, where d_n is the nEDM, E the electric field, and j is a Bessel Function. Thus, the value of $x = x_c$ that yields ‘critical dressing’, or equal precession of the frequencies, is changed. One thus measures the value of x_c versus the electric field direction to extract a neutron EDM signal.

Estimates show that one can obtain densities of both UCN and polarized ^3He in the measurement cell that are comparable to those that will be obtained in the main experiment. Thus this apparatus will allow us to fully test the spin dressing technique using both polarized UCN and polarized ^3He simultaneously in a measurement cell. The development of the necessary electronics and operating procedures will represent a substantial contribution to the main experiment and is substantially expected to reduce the time to data collection. In addition, the proposed feedback system will remove the effects of the pseudo-magnetic field.

Measurement of the ‘Trajectory Correlation Function’ for Systematic Error Quantification

Relaxation effects (T_1 and T_2) and the so-called geometric phase systematic error all depend on the trajectory correlation functions of the ^3He and UCN. These correlation functions form a family related by differentiation (or integration) so measurement of one serves to determine the whole family.

While theoretically one does not expect the wall collisions to have a large impact on the results, this will be tested empirically. Unexpected effects like rather long residence times of the particles in surface pores for instance, could affect the results, so it is important to have an independent measure of these correlation functions.

Detection of the ^3He Pseudomagnetic Field in Search of Possible Double Resonance Effects

The nEDM measurement can be influenced by the ‘pseudo-magnetic field’ discussed above. This field arises from the spin-dependent coherent scattering cross-section, which leads to an energy shift that is spin dependent and thus appears as a magnetic field. The pseudomagnetic field is not directly affected by the application of an electric field, but can be the source of precession frequency fluctuations and hence extra noise in the system. The influence of the pseudomagnetic field can be reduced by ensuring that the magnetometer spins have no component along the static magnetic field, which is possible by careful control of the spin flip pulses.

Such pseudomagnetic fields have appeared in other EDM experiments, for example, in a ^{129}Xe experiment where the field was of order 1 mHz due to the presence of spin polarized rubidium that was used to polarize and detect the ^{129}Xe spin precession[16]. This frequency, as an EDM in a 5 kV/cm field that was used in the experiment, corresponds to 10^{-22} e-cm, while the final experiment sensitivity is in the 10^{-26} e-cm range. This level of discrimination results simply from the fact that the electric field does not directly affect the

pseudomagnetic field, and the spin of the rubidium was approximately orthogonal to the applied static magnetic field.

Development of Techniques for NMR Imaging of ^3He

The idea of the ^3He co-magnetometer is that it should sample the magnetic field in the same way that the field is seen by the UCN, i.e. both species should have a uniform density. However the density distribution of the ^3He can be distorted by heat currents flowing in the measurement cell. The phonons constituting the heat currents act as a wind on the ^3He atoms and cause them to move with the heat current. Diffusion against this current results in an equilibrium inhomogeneous density distribution.

Standard NMR techniques can be used to study these effects. Although our NMR frequency is quite low, it has been shown that with reasonable gradients, resolutions on the order of 1 cm can be achieved, sufficient for our measurement cells. Note that these measurements can be carried out without UCN, so they can be performed with a considerably higher ^3He density than that in the nEDM search.

Study Techniques for Reversing $\sigma_{^3\text{He}}$, σ_{UCN} and B_0 and Other Ancillary Measurements

Establishing the experimental parameters for reversing the spins and magnetic fields will take a considerable length of time during the commissioning phase of the apparatus. Developing these techniques at PULSTAR will provide an environment where one can perform a more complete study of these reversals without the external time constraints imposed by the project schedule.

The apparatus can also be used for additional tests on actual measurement cells that could be installed in the main apparatus. These items include for example UCN and/or ^3He storage and depolarization studies to optimize measurement cell materials and fabrication techniques as well serving as a test bed for new cell designs and/or trouble shooting cells that don't work in main apparatus.

IV. ^3He SPIN TRANSPORT AND INJECTION INTO LIQUID HELIUM

Polarized ^3He is used as a co-magnetometer in the nEDM experiment. This helium, produced using an atomic beam source, is infused into a bath of ~ 400 mK liquid helium that resides above the measurement cells. The transport of ^3He spins through magnetic field gradients has been simulated in order to demonstrate whether nearly 100 % polarized ^3He can maintain its polarization after injection from the atomic-beam source (ABS) into the collection volume in the nEDM experiment. In addition, a test of the ^4He -film burner is envisioned in order to demonstrate whether the film burner can maintain low ^4He vapor pressure in the injection line. This is crucial for ^3He to be successfully injected into the collection volume.

^3He Depolarization Simulations

Simulations have been performed to calculate how the spin precesses as the ^3He atoms travel inside the transport tube from the ABS exit interface to the collection volume. The 4th order Runge-Kutta method was used to solve the Bloch equation, which describes a spin \vec{M} precessing in a magnetic field \vec{B} . The vector form of the Bloch equation is written as $\frac{d\vec{M}(t)}{dt} = \gamma \vec{M}(t) \times \vec{B}(\vec{r})$ where \vec{r} is the position vector of the spin. At $t = 0$, the spins are at the ABS exit interface, and at $t = T$ the spins have traveled to the collection volume. By integrating the Bloch equation over this timeframe, one can obtain the magnetization $\vec{M}(T)$ of spins inside the collection volume. Because the magnetic field inside the collection volume is in the \hat{x} direction, the \hat{x} component of the spin, i.e. M_x , gives the polarization.

Different magnetic-field distributions $\vec{B}(\vec{r})$ give different final ^3He polarizations in the collection volume. The goal of the simulation was to assist in the design of the magnetic field so that the final polarization of ^3He is at least 95 %. The latest magnetic-field design (March 2010 from Arizona State University) has two current configurations: one with all the magnetic-field currents in the positive direction, so that the B field in the collection volume is in the $+\hat{x}$ direction, and the other with all the currents reversed, so that the B field is in the $-\hat{x}$ direction. Nearly 10,000 events have been simulated for each configuration, giving a statistical uncertainty of ~ 1 %. The polarization of ^3He as a function of position was calculated. Two regions leading to polarization loss were identified. One is at the ABS exit and is due to the strong and irregular fringe fields of the ABS; the other is close to the collection volume, where the spins start to rotate from the ^3He injection direction to the \hat{x} direction in order to match the holding field inside the collection volume. The final polarization in the collection volume is calculated to be 76 % for the positive current configuration, and 79 % for the negative current configuration.

The nEDM experiment requires > 95 % polarization of ^3He in the collection volume, thus improvements

in the magnetic field design are required. The polarization loss at the exit of the ABS can be reduced by increasing the transport-magnetic-field strength so that spins can follow field changes more easily. Meanwhile, the spin rotation should also be carried out at high fields near the ABS exit, instead of at low fields, which cause polarization loss. Once spin rotation is complete, the transport field needs to be tapered down from a few hundred gauss to several hundred milligauss to match the holding field in the collection volume. Presently, the University of Kentucky group is working on a new magnetic-field design that incorporates the features mentioned above.

³He Injection/Film Burner Tests

The injection test was designed to determine whether polarized ³He can successfully be injected into the liquid helium-filled collection volume in the nEDM experiment. A successful injection critically depends on having a low pressure inside the injection tube to minimize scattering of the ³He atoms from the ⁴He vapor. Superfluid-⁴He film that creeps up from the collection volume into the injection tube and evaporates will increase the pressure inside the tube. Hence, a film burner was designed to control the superfluid-⁴He film so that it does not vaporize into the flight tube. The ⁴He-film burner has been manufactured and is ready to be tested. Most of the parts for the injection test—including the 1.2 kG tri-coil magnet, the gas handling system, plus the ABS and pulsed NMR system—have been built and, will be whenever possible, tested.

The injection tests are presently delayed due to high voltage R&D activities utilizing cryogenic components required for these tests. On a shorter timescale however, we have shifted focus to carry out a smaller scale experiment in collaboration with the University of Illinois at Urbana-Champaign that will test just the film burner itself. In this film-burner test, no ³He will be injected, and thus less cooling power will be required so that a smaller dilution refrigerator (DR) can be utilized.

V. NEUTRON BEAMLINE DESIGN

As part of the Fundamental Neutron Physics Beamline (FnPB) construction project at the SNS, TUNL has been in charge of modeling the neutronics performance of both the polychromatic and the 0.89 nm beam lines. As a natural extension to this effort, in collaboration with the University of Kentucky, we are working to extend this work so as to benchmark the flux measurements to the nEDM experiment in order to provide a more accurate estimate of the neutron fluence into the measurement cells as well as optimize the design of the neutron guides.

The FnPB facility includes two neutron beamlines: a polychromatic cold beam and a 0.89 nm monochromatic beam. For the former, cold neutrons from the liquid hydrogen moderator are transported approximately 15 m through a series of 10 cm × 12 cm straight and curved guides to the experimental area in the main SNS target building. For the latter, a 0.89 nm monochromatic beam is reflected out of the polychromatic beam by a stage-1, potassium-intercalated graphite monochromator, followed by a second stage-1, rubidium-intercalated graphite monochromator configured in a double-crystal design. The resulting beam is almost parallel to the polychromatic beam and directed towards the external nEDM building. Measurements of the neutron flux were made at the end of the cold beamline and at the end of the 8 m expansion guide on the 0.89 nm beamline[17].

Simulations of the neutron transport to the nEDM measurement cells were performed using both the MCSTAS and GEANT4 codes[18, 19]. The neutron flux was measured at the end of the cold guide in 2009[17]. When compared with the two simulations which are consistent with each other, it indicates that the measured flux at 0.89 nm is roughly a factor of 20 % higher than the flux predicted by simulation. Similar comparisons were made to the measured neutron flux at the end of the 8 m expansion horn on the 0.89 nm guide as well. These simulations indicated that the measured flux at 0.89 nm is less than the predicted value by a factor of roughly 2.4. Based on the good agreement with the cold beam, we postulated that this difference arises from unknown loss mechanisms within the monochromator crystals.

The neutron flux to the nEDM measurement cells was simulated for each of the two beamlines. For the polychromatic line, the last 3.5 m of existing straight guide was removed and replaced by a ballistic guide/polarizing system extending to the cells. The new guide geometry consists of a 10 × 12 cm² polarizing bender, 4.25 m long, 22 m radius, and 5 channels, followed by an 8 m long ballistic expansion horn that expands from the 10 × 12 cm² entrance to a 30 × 30 cm² exit. The expansion horn is followed by a 30 × 30 cm², $m = 1.5$ straight guide, 14.15 m long that extends from the exit of the expansion horn to the entrance of the beam splitter. The splitter is two almost parallel, 6 m long converging guides that have a 15 × 30 cm² entrance and 7 × 14 cm² exit. The midpoint of each measurement cell is 0.78 m downstream of the exit of the guide.

The neutron flux into the measurement cells was calculated using both codes, although polarization calculations in the polarizing bender are presently only calculated using GEANT4 and these polarizations are used to

scale the MCSTAS results. Agreement between the two codes is of the order of a few percent. At the nominal operating power of 2 MW, we estimate the 0.89 nm flux using the cold line to be

$$\frac{d\phi_{cold}}{d\lambda} = 9.8 \times 10^6 \text{ n/s/cm}^2/\text{\AA} \quad \text{and for the UCN line} \quad \frac{d\phi_{UCN}}{d\lambda} = 2.0 \times 10^6 \text{ n/s/cm}^2/\text{\AA}. \quad (1)$$

These fluxes correspond to UCN production rates in the measurement cells of

$$\frac{dN_{UCN}}{dt} = 1290 \text{ UCN/s} \quad \text{and for the UCN line} \quad \frac{dN_{UCN}}{dt} = 263 \text{ UCN/s}. \quad (2)$$

One can see that the flux using the polychromatic line is a factor of five larger than the monochromatic line. The collaboration has decided to utilize the polychromatic line for the nEDM measurements and thus additional optimization of this beamline is underway.

VI. CRYOGENIC DESIGN AND TESTING

The neutron electric dipole moment (nEDM) experiment requires cooling a 1 m³ volume of superfluid liquid helium to an operating temperature between 0.25 K and 0.45 K. This central volume encloses a separate target volume of superfluid in which 0.89 nm neutrons from the SNS are down-scattered into UCNs and confined in an acrylic measurement cell. The central volume and target, plus associated experimental services, are cooled by a high-flow ³He-⁴He dilution refrigerator. The vacuum container enclosing the cryogenic systems is called the cryovessel and is cooled using liquid helium through a permanent connection to a helium liquefier system. TUNL is responsible for the design and construction of the cryovessel with its enclosed 80 K and 4 K thermal shields, the helium liquefier system, the ³He-⁴He dilution refrigerator, the central volume, and the associated vacuum hardware, cryogenic sensors, and controls.

Helium Liquefier System

A dedicated system with a helium liquefier and helium flow to the cryovessel has been adopted. Our initial design coupled a Linde L70 liquefier directly to the cryovessel. Recently, we have developed a Memorandum of Understanding with the SNS for the construction and operation of a larger common helium liquefier that will serve the SNS users, the nEDM experiment, and another proposed SNS user project. In this plan, the nEDM experiment will receive liquid helium and return cold or warm helium gas to a liquefier located in a building adjacent to the FnpB external building. This arrangement should improve the reliability of helium supply to the nEDM cryovessel and reduce maintenance requirements. The nEDM experiment will maintain a large liquid-helium (LHe) storage volume and piping system to connect to the cryovessel. The design of the flow system is driven by the need to fill the 1 m³ central volume with liquid helium at 4 K and to cool the rest of the cryovessel as quickly and efficiently as possible. To reduce vibrations, the 80 K thermal shields will be cooled by a positive pressure flow of liquid nitrogen driven by an external cryogenic pump and phase separator.

³He-⁴He Dilution Refrigerator

Cooling the central volume and target cell from 4 K to 0.25 K requires the use of a large ³He-⁴He dilution refrigerator (DR). This DR must provide a cooling power of 80 mW at a mixing chamber temperature of 300 mK. As such, the dilution refrigerator will be among the most powerful ever built.

We have studied configurations of several high cooling power machines, many of them used for polarized nuclear target systems. We also contracted Janis Research to produce a design study for the cryostat, pumping stacks and gas-handling system for the nEDM dilution refrigerator. The final design is meant to operate at a ³He flow rate of 20 to 30 mmol/sec. This high flow rate requires a gas heat exchanger – a separator – which uses helium vapor from the entrainment volume to cool the incoming ³He. There is also a 1.5 K liquid helium evaporator to liquefy the ³He before it reaches the still of the dilution refrigerator.

Working with ORNL, we have modified the design so that it can function in addition as a ³He or ⁴He evaporative refrigerator above 1 K. This is achieved by adding a flow circuit to recirculate ⁴He and a “stopper” below the still that can short-circuit the low-temperature heat exchangers and increase the effective pumping speed of the recirculation system. Final design of the dilution refrigerator is underway.

Cryovessel

The cryovessel serves not only to provide the vacuum and 4 K cryogenic environment for the experiment, it is the primary safety envelope for the entire experiment. As such it must be an ASME certified vacuum vessel and meet the SNS safety requirements.

The cryovessel consists of an outer vacuum enclosure with internal 80 K and 4 K thermal shields. We have modeled the heat inputs into the liquid nitrogen (LN) cooled shield and the 4 K helium-cooled shield of the cryovessel. The shields will be insulated by vacuum and multiple layers of aluminized mylar superinsulation. The shields will be constructed of aluminum alloy with multiple cooling tubes for LN or He gas welded to the surfaces. Because of the overall heat load to the cryovessel, an 80 K LN cooled shield was chosen in preference to a He gas-cooled intermediate shield. The 4 K shield will be cooled through a thermosyphon arrangement, where evaporating helium from the entrainment volume is cycled through the shield and then to the cold return line of the helium liquefier. In the design process, we have calculated scenarios for cooling the cryovessel and contents to 4 K and the final operating temperatures for the nEDM experiment. Because of the large masses of the components and the 1 m³ volume of LHe in the insulation volume, a cooldown will require approximately 3–4 weeks.

Because the cryovessel will contain about 1 m³ of superfluid liquid helium it presents unusual safety challenges. In addition to the DOE requirement that the vessel be an ASME certified vacuum vessel, it must also provide the safety envelope for the experiment under accident scenarios where the vacuum is lost and the liquid helium is vaporized. We are working with personnel at the SNS to develop a suitable safety plan, calculate the effects of possible pressure release scenarios, and design mitigating vent and pressure release devices. Although the cryovessel will be constructed in accordance with ASME Pressure Code Section VIII, the neutron windows and other external connections, must be separately designed and approved. The pressure releases must assure that no gases are released toward the neutron guides and that the internal cryovessel does not exceed its maximum allowable working pressure of about 1.5 atm.

Cryogenic Test Facilities

In the nEDM experiment, tubes with diameters of 0.5 inch and larger will connect volumes of superfluid liquid helium under vapor pressure at $T \leq 0.5$ K to volumes at temperatures above the superfluid transition temperature. It is well-known that there can be large heat flows due to the flow of superfluid film up the tube as well as to the reflux of warm gas caused by the evaporation of the film at higher temperatures[20, 21]. The details of the reflux process have implications for the design of the ⁴He film burners and of the heat sinking of the tubes in the nEDM apparatus. Previous theoretical and experimental results on this process have described relatively thin tubes, much smaller than those planned for the nEDM configuration. Using calculations based on the Cornut model, we have prepared a sample cell for measurements of the superfluid heat flows in tubes of various lengths and diameters. This will be an independent test of the reflux model extended to the temperature range of importance to the nEDM experiment.

We have constructed at TUNL a cryogen-free cryostat and vacuum system for the testing of seals and construction materials to temperatures below the helium superfluid transition. It will be possible to cool half-scale prototypes as large as 21 inches in diameter and test them in vacuum. A Sumitomo 1.5 W (at 4 K) RDK-415D Gifford-McMahon cryocooler with an F-50 water-cooled compressor refrigerates the test volume. A separate sealed helium-evaporator insert into the test volume will continue the cooling to less than 2 K. The fixtures being tested will be filled with superfluid helium at 1 atmosphere of pressure to mimic the nEDM operating conditions. Initially we are testing the cooling and sealing of G-10 composite flanges with o-rings made from 0.005 inch thick Kapton foils[22]. These will be followed by tests of sealing and diffusion through candidate materials for neutron windows.

VII. DATA ACQUISITION/SLOW CONTROLS

TUNL has taken responsibility for the design and implementation of both the fast waveform digitization system as well as the slow controls for the nEDM project.

The nEDM scintillation signal as a function of time is a measure of the beat frequency between the neutron and ³He precession rates. The Data Acquisition (DAQ) system will be triggered by prompt coincidence signals from an array of photomultiplier tubes which will be digitized using a series of transient waveform digitizers to capture both the prompt and after-pulse scintillation signals for of order a microsecond after each trigger event. Event rates are expected to be of order 1 kHz. As an initial effort in the design of this system, we have set up a 100 MHz VME digitizer and used it to capture a sample signal consisting of a main pulse with afterpulses. We plan additional characterization of this system prior to the procurement of the 1 GHz system that is envisioned for the main apparatus.

The proposed slow control system is designed around the use of VME crates with VxWorks as the on-board operating system. EPICS (Experimental Physics and Industrial Controls System) software which is a standard network-based control package that is used at many major accelerator facilities (including ORNL/SNS) will

provide the interface between the many commercially available devices and the VME system. EPICS is open source software that operates in a distributed network environment and is available to users at no cost.

The nEDM apparatus and measurement cycles will require control or monitoring of order 1,000 parameters and status values. The present plan is to develop five individual subsystems that will be built and tested at different sites as the components they control are being developed. As a distributed-control environment, EPICS is ideally suited for this application because the individual subsystem development can proceed independently up until the integration step at final assembly and testing at the SNS.

VIII. SUMMARY

The wide range of research backgrounds, technical expertise and numbers of graduate students within the TUNL research community enable and stimulate a broad collaborative research program that spans several frontier areas in nuclear physics. TUNL faculty strive to continue their emphasis on maintaining a research environment that is conducive to graduate education by engaging students in all aspects of research from concept development through data interpretation and dissemination of results. Collaboration of the research groups from the consortium universities along with the research infrastructure at TUNL enable TUNL groups to not only take significant responsibilities in projects such as the nEDM, but also contribute in a wide range of areas. In addition, the small-group environment at TUNL provides opportunities for students to work closely with postdocs and faculty, to have hands-on research experiences, and ultimately grow to provide leadership roles in their individual projects.

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